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Indian Standard

DETERMINATION OF POWER LOSSES IN HIGH-VOLTAGE DIRECT CURRENT (HVDC) CONVERTER STATIONS

ICS 29.200

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BUREAU OF INDIAN STANDARDS
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NEW DELHI 110002

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Price Group 11

HVDC Power Systems Sectional Committee, ET 40

NATIONAL FOREWORD

This Indian Standard which is identical with IEC 61803 (1999) 'Determination of power losses in high-voltage direct current (HVDC) converter stations' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendations of the HVDC Power Systems Sectional Committee and approval of the Electrotechnical Division Council.

The text of the IEC Standard has been approved as suitable for publication as an Indian Standard without deviations. Certain terminology and conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.

b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

In this adopted standard, reference appears to certain International Standards for which Indian Standards also exist. The corresponding Indian Standards which are to be substituted in their respective places are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60289 (1988) Reactors	IS 5553 (Part 1) : 1989 Reactors — Specification: Part 1 General (*first revision*)	Technically Equivalent
	IS 5553 (Part 2) : 1990 Reactors — Specification: Part 2 Shunt reactors (*first revision*)	
	IS 5553 (Part 3) : 1990 Reactors — Specification: Part 3 Current limiting reactors and neutral earthing reactors (*first revision*)	
	IS 5553 (Part 4) : 1989 Reactors — Specification: Part 4 Damping reactors (*first revision*)	
	IS 5553 (Part 5) : 1989 Reactors — Specification: Part 5 Tuning reactors (*first revision*)	
	IS 5553 (Part 6) : 1990 Reactors — Specification: Part 6 Earthing transformers (Neutral couplers) (*first revision*)	
	IS 5553 (Part 7) : 1990 Reactors — Specification: Part 7 Arc suppression reactors (*first revision*)	
	IS 5553 (Part 8) : 1990 Reactors — Specification: Part 8 Smoothing reactors (*first revision*)	

(*Continued on third cover*)

Indian Standard

DETERMINATION OF POWER LOSSES IN HIGH-VOLTAGE DIRECT CURRENT (HVDC) CONVERTER STATIONS

1 Scope

This International Standard applies to all line-commutated high-voltage direct current (HVDC) converter stations used for power exchange in utility systems. This standard presumes the use of 12-pulse thyristor converters but can, with due care, also be used for 6-pulse thyristor converters.

In some applications, synchronous compensators or static var compensators (SVC) may be connected to the a.c. bus of the HVDC converter station. The loss determination procedures for such equipment are not included in this standard.

This standard presents a set of standard procedures for determining the total losses of an HVDC converter station. Typical HVDC equipment is shown in figure 1. The procedures cover all parts, except as noted above, and address no-load operation and operating losses together with their methods of calculation which use, wherever possible, measured parameters.

Converter station designs employing novel components or circuit configurations compared to the typical design assumed in this standard, or designs equipped with unusual auxiliary circuits that could affect the losses, shall be assessed on their own merits.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60076-1:1993, *Power transformers – Part 1: General*

IEC 60289:1988, *Reactors*

IEC 60633:1998, *Terminology for high-voltage direct current (HVDC) transmission*

IEC 60700-1:1998, *Thyristor valves for high voltage direct current (HVDC) power transmission – Part 1: Electrical testing*

IEC 60747-6:1983, *Semiconductor devices – Discrete devices – Part 6: Thyristors*

IEC 60871-1:1997, *Shunt capacitors for a.c. power systems having a rated voltage above 1 000 V – Part 1: General performance, testing and rating – Safety requirements – Guide for installation and operation*

3 Definitions and symbols

For the purpose of this International Standard, the following definitions apply:

3.1 Definitions

3.1.1
auxiliary losses
the electric power required to feed the converter station auxiliary loads. The auxiliary losses depend on whether the station is in no-load operation or carrying load, in which case the auxiliary losses depend on the load level

3.1.2
no-load operation losses
the losses produced in an item of equipment with the converter station energized but with the converters blocked and all station service loads and auxiliary equipment connected as required for immediate pick-up of load

3.1.3
load level
this term specifies the direct current, direct voltage, firing angle, a.c. voltage, and converter transformer tap-changer position at which the converter station is operating

3.1.4
operating losses
the losses produced in an item of equipment at a given load level with the converter station energized and the converters operating

3.1.5
rated load
this load is related to operation at nominal values of d.c. current, d.c. voltage, a.c. voltage and converter firing angle. The a.c. system shall be assumed to be at nominal frequency and its 3-phase voltages are nominal and balanced. The position of the tap-changer of the converter transformer and the number of a.c. filters and shunt reactive elements connected shall be consistent with operation at rated load, coincident with nominal conditions

3.1.6
total station losses
the total station loss is the sum of all operating or no-load operation losses and the corresponding auxiliary losses

3.2 Letter symbols

α	firing delay angle, in radians (rad)
μ	commutation overlap angle, in radians (rad)
f	a.c. system frequency, in hertz (Hz)
I_d	current in the bridge d.c. connection, in amperes (A)
I_n	harmonic r.m.s. current of order n, in amperes (A)
L_1	the inductance, in henrys (H), referred to the valve winding, between the commutating voltage source and the point of common coupling between star- and delta-connected windings. L_1 shall include any external inductance between the transformer line-winding terminals and the point of connection of the a.c. harmonic filters
L_2	the inductance, in henrys (H), referred to the valve winding, between the point of common coupling between star- and delta-connected windings, and the valve. L_2 shall include the saturated inductance of the valve reactors
m	electromagnetic notch coupling factor, $m = L_1/(L_1 + L_2)$
n	harmonic order
N_t	the number of series-connected thyristors per valve
P	power loss in an item of equipment, in watts (W)
Q_n	quality factor at harmonic order n
R	resistance value, in ohms (W)
U_d	direct voltage, in volts (V)
U_n	harmonic r.m.s. voltage of order n, in volts (V)
U_{vo}	r.m.s. value of the phase-to-phase no-load voltage on the valve side of the converter transformer, in volts (V)
X_n	inductive reactance at harmonic order n, in ohms (Ω)

4 General

4.1 Introduction

Suppliers need to know in detail how and where losses are generated, since this affects component and equipment ratings. Purchasers are interested in a verifiable loss figure which allows equitable bid comparison and in a procedure after delivery which can objectively verify the guaranteed performance requirements of the supplier.

As a general principle, it would be desirable to determine the efficiency of an HVDC converter station by a direct measurement of its energy losses. However, attempts to determine the station losses by subtracting the measured output power from the measured input power should recognize that such measurements have an inherent inaccuracy, especially if performed at high voltage. The losses of an HVDC converter station at full load are generally less than 1 % of the transmitted power. Therefore, the loss measured as a small difference between two large quantities is not likely to be a sufficiently accurate indication of the actual losses.

In some special circumstances it may be possible, for example, to arrange a temporary test connection in which two converters are operated from the same a.c. source and also connected together via their d.c. terminals. In this connection, the power drawn from the a.c. source equals the losses in the circuit. However, the a.c. source must also provide var support and commutating voltage to the two converters. Once again, there are practical measurement difficulties.

In order to avoid the problems described above, this standard standardizes a method of calculating the HVDC converter station losses by summing the losses calculated for each item of equipment. The standardized calculation method will help the purchaser to meaningfully compare the competing bids. It will also allow an easy generation of performance curves for the wide range of operating conditions in which the performance has to be known. In the absence of an inexpensive experimental method which could be employed for an objective verification of losses during type tests, the calculation method is the next best alternative as it uses, wherever possible, experimental data obtained from measurements on individual equipment and components under conditions equivalent to those encountered in real operation.

It is important to note that the power loss in each item of equipment will depend on the ambient conditions under which it operates, as well as on the operating conditions or duty cycles to which it is subjected. Therefore, the ambient and operating conditions shall be defined for each item of equipment, based on the ambient and operating conditions of the entire HVDC converter station.

4.2 Ambient conditions

A set of standard reference ambient conditions shall be used for determining the power losses in HVDC converter stations.

4.2.1 Outdoor standard reference temperature

An outdoor ambient dry bulb temperature of 20 °C shall be used as the standard reference temperature for determining the total converter station losses. The equivalent wet-bulb temperature (where necessary) shall be defined by the purchaser.

4.2.2 Coolant standard reference temperature

Where forced cooling is used for equipment, the flow rate and temperature of the coolant can influence the temperature rise and associated losses of that equipment. Therefore, the coolant temperatures and flow rates established by the purchaser and the supplier shall be used as a basis for determining the losses.

4.2.3 Standard reference air pressure

The reference air pressure to be used for the evaluation of total converter station power losses shall be the standard atmospheric pressure (101,3 kPa) corrected to the altitude of the installation in question.

4.3 Operating parameters

The losses of an HVDC converter station depend on its operating parameters.

The losses of HVDC converter stations are classified into three categories, termed the no-load operation losses, operating losses and auxiliary losses.

The operating losses and auxiliary losses are affected by the load level of the station because the numbers of certain types of energized equipment (for example harmonic filters and cooling equipment) may depend upon the load level and because losses in individual items of equipment themselves vary with the load level.

HVDC converter station losses shall be determined for nominal (balanced) a.c. system voltage and frequency, symmetrical impedances of the converter transformer and symmetrical firing angles. The transformer tap-changer shall be assumed to be in the position corresponding to nominal a.c. system voltage.

The operating losses shall be determined for the load levels specified by the purchaser, or at rated load if no such conditions are specified. For each load level, the valve-winding a.c. voltage, d.c. current, converter firing angle, shunt compensation and harmonic filtering equipment shall be consistent with the respective load level and other specified performance requirements, relating, for example, to harmonic distortion and reactive power. Cooling and other auxiliary equipment, as appropriate to the standard reference temperature (see 4.2.1 and 4.2.2), shall be assumed to be connected to support the respective load level.

For the no-load operation mode, converter transformers shall be energized and the converters blocked. All filters and reactive power compensation equipment shall be assumed to be disconnected except for those which are required to sustain operation at zero load in order, for example, to meet the specified reactive power requirements. Station service loads and auxiliary equipment (e.g. cooling-water pumps) shall be assumed to be connected as required for immediate pick-up of load for the converter station.

5 Determination of equipment losses

5.1 Thyristor valve losses

The loss production mechanisms applicable when the valves are blocked (no-load operatio losses) are different from those applicable in normal operation (operating losses). Operating losses are dealt with in subclauses 5.1.1 to 5.1.10, and no-load operation losses are dealt with in 5.1.11. Auxiliary losses are dealt with in 5.8.

A simplified three-phase diagram of an HVDC 12-pulse converter is shown in figure 2. Individual valves are marked in the order of their conduction sequence.

A simplified equivalent circuit of a typical valve is shown in figure 3. Symbol t combines together the effects of N_t thyristors connected in series in the valve. C_{AC} and R_{AC} are the corresponding combined values of R-C damping circuits used for voltage sharing and overvoltage suppression. R_{DC} represents d.c. grading resistors and other resistive components which incur loss when the valve blocks voltage. It also includes the effects of the thyristor leakage current (see 5.1.4 and 5.1.11). C_s includes both stray capacitances and surge distribution capacitors (if used). L_s represents saturable reactors used to limit the di/dt stresses to safe values and to improve the distribution of fast rising voltages. R_s represents the resistances of the current conducting components of the valve such as the busbars, contact resistances, resistance of the windings of the saturable reactors etc. Power losses in the valve surge arrester (not shown) shall be neglected.

Figure 4 shows, as an example, current and voltage waveforms of valve 1 (according to figure 2) operating in rectifier and inverter modes. In the example shown, the firing instants of the valves of the upper bridge are delayed by 30° with respect to the valves of the lower bridge due to the phase shift between the two secondaries. For each valve, the length of the conduction intervals is 130° ($2\pi/3 + \mu$). During commutations the valve current is assumed, for this standard, to be changing linearly whereas in reality the valve currents follow portions of sine waves. This simplification has negligible effect on the resulting losses, while the trapezoidal waveform significantly simplifies the calculations. The voltage blocked by the valve shows notches caused by commutations between individual valves.

5.1.1 Thyristor conduction loss per valve

This loss component is the product of the conduction current $i(t)$ and the corresponding ideal on-state voltage as shown in figures 5 and 6. Formula P_{V1a} shall be used provided that the d.c. bridge current is well smoothed. In the event that the root sum square value of the d.c. side harmonic currents, determined in accordance with clause A.4 (annex A), exceeds 5 % of the d.c. component, formula P_{V1b} shall be used instead.

$$P_{V1a} = \frac{N_t \times I_d}{3}\left[U_0 + R_0 \times I_d \times \left(\frac{2\pi - \mu}{2\pi}\right)\right]$$

$$P_{V1b} = \frac{N_t \times I_d \times U_0}{3} + \frac{N_t \times R_0}{3}\left(I_d^2 + \sum_{n=12}^{n=48} I_n^2\right)\left(\frac{2\pi - \mu}{2\pi}\right)$$

where

U_0 is the current-independent component of the on-state voltage of the average thyristor (see note below), in volts;

R_0 is the slope resistance of the on-state characteristic of the average thyristor (see note below), in ohms;

I_n is the calculated r.m.s. value of the nth harmonic current in the bridge d.c. connection according to clause A.4, in amperes.

NOTE – U_0 and R_0 (see figure 5) are determined from the fully spread on-state voltage measured at the appropriate current and junction temperature. The average value of U_0 and R_0 is obtained from production records of the thyristors manufactured for the specific project at 100 % and 50 % of nominal d.c. current. The temperature dependence of U_0 and R_0 is established from type tests or routine tests on a statistically significant number of the thyristors employed, and is used, where necessary, to correct U_0 and R_0 to the appropriate service junction temperature. If parallel connection of p thyristors is employed, the appropriate 100 % current is the nominal d.c. bridge current divided by p. The calculated result is then multiplied by p.

5.1.2 Thyristor spreading loss per valve

This loss component is an additional conduction loss of the thyristors arising from the delay in establishing full conduction of the silicon after the thyristor has been turned on. The additional loss is the product of the current and the voltage by which the thyristor voltage exceeds the ideal thyristor on-state voltage drop (see the hatched area in figure 6).

$$P_{V2} = N_t \times f \times \int_0^{t_1} \left[u_B(t) - u_A(t) \right] \times i(t) dt$$

where

t_1 is the length of the conduction interval, in seconds, which is given by:

$$t_1 = \frac{\frac{2}{3}\pi + \mu}{2\pi f};$$

$u_B(t)$ is the instantaneous on-state voltage, in volts, of a thyristor whose fully spread on-state voltage is typical for the thyristors used. The instantaneous on-state voltage shall be determined for the appropriate junction temperature measured with a trapezoidal current pulse exhibiting the correct amplitude and commutation overlap periods (see figures 5 and 6);

$u_A(t)$ is the calculated instantaneous on-state voltage of the average thyristor at the same junction temperature for the same current pulse but with the conducting area fully established throughout the conduction, as derived from its on-state characteristic represented by U_0 and R_0 only (see figure 6);

$i(t)$ is the instantaneous current in the thyristor, in amperes.

NOTE – Instantaneous on-state voltage data, including the effects of spreading, are usually not available from production records. Measurements of typical thyristor on-state voltage, including spreading, should therefore be obtained during the valve periodic firing and extinction type test (see IEC 60700-1) or, alternatively, from a separate laboratory test on a statistically significant number of thyristors.

5.1.3 Other conduction losses per valve

These are the conduction losses in the main circuit of the valve due to components other than the thyristors.

$$P_{V3} = \frac{R_s \cdot I_d^2}{3} \left(\frac{2\pi - \mu}{2\pi} \right)$$

where

R_s is the d.c. resistance of the valve terminal-to-terminal circuit excluding the thyristors, in ohms (see figure 3).

The value of R_s is determined by direct measurement on a representative valve section that includes all elements of the main circuit of a valve in the correct proportions, but in which the thyristors have been replaced by copper blocks of the appropriate dimensions and with contacts treated in the same way as for real thyristors. Alternatively, the resistance may be calculated, in which case the calculation methods shall be documented.

5.1.4 D.C. voltage-dependent loss per valve

This loss component is the loss in the shunt resistance R_{DC} of the valve (see figure 3), arising from the voltage which appears between valve terminals during the non-conducting interval (see figure 4). It includes losses due to thyristor off-state and reverse leakage, losses in d.c. grading resistors, other resistive circuits and elements connected in parallel with the thyristors, resistance of the coolant in coolant pipes, resistivity effects of the structure, fibre optics, etc.

$$P_{V4} = \frac{U_{v0}^2}{2\pi\ R_{DC}} \left\{ \frac{4}{3} + \frac{\sqrt{3}}{4}\left[\cos(2\alpha) + \cos(2\alpha + 2\mu)\right] + \frac{6m^2 - 12m - 7}{8}\left[\sin(2\alpha) - \sin(2\alpha + 2\mu) + 2\mu\right] \right\}$$

where

R_{DC} is the effective off-state d.c. resistance of a complete valve determined by measuring the current drawn during the valve terminal-to-terminal d.c. voltage type test (see IEC 60700) in ohms. If a type test is not performed on the thyristor valve, R_{DC} shall be determined by reference to a previous type test (see also note 2 below);

$m = L_1/(L_1 + L_2)$;

L_1 is the inductance, in henrys, referred to the valve winding, between the commutating voltage source and the point of common coupling between star- and delta-connected windings. L_1 shall include any external inductance between the transformer line-winding terminals and the point of connection of the a.c. harmonic filters (see figure 7);

L_2 is the inductance, in henrys, referred to the valve winding, between the point of common coupling between star- and delta-connected windings, and the valve. L_2 shall include the saturated inductance of the valve reactors (see figure 7).

The value of L_2 shall be the same for both secondaries ($L_{2d} = L_{2y}$) (see notes 3 and 4 below).

NOTE 1 – The equation for P_{V4} is valid for $\mu < \pi/6$ (30°) only.

NOTE 2 – Since the thyristor resistive leakage current is usually much higher at operating temperatures than at the prevailing ambient air temperature, it is either necessary to heat the thyristors of the valve to the correct operating temperature before the measurement of R_{DC} is taken or to make later corrections to the measured value using the average thyristor data obtained separately, to include the mentioned temperature effect (see also 5.1.10). The same pertains to the liquid coolant.

NOTE 3 – The value of m quantifies the effects of inductive coupling between the two secondaries of the converter transformer. It determines the magnitude of the notches caused by the commutation in the other bridge (notches from 1' to 3' and from 4' to 6' in figure 4). If $m = 0$, then there is no coupling between the two bridges and the notches from 1' to 3' and from 4' to 6' disappear altogether. The notches in figure 4 correspond to $m = 0{,}2$.

NOTE 4 – Values of L_1 and L_2 are obtained from the short-circuit impedance measurements on the converter transformers, and by adding any external inductances as required. The value of L_1 includes any external common inductance (such as power line carrier filters) between the point of common coupling and the commutation voltage source. In cases where no a.c. harmonic filters are connected, L_1 also includes the a.c. system impedance. When separate transformers supply the star and delta bridges and no additional line-side inductance is included, $L_1 = 0$, hence $m = 0$. When a three-winding transformer construction is employed a common winding impedance and mutual coupling effects of the two secondary windings give non-zero values for L_1, which may be either positive or negative. For more complicated transformer arrangements, such as filters connected to a tertiary winding, the values of L_1 and L_2 must be determined with care.

5.1.5 Damping loss per valve (resistor-dependent term)

This loss component depends on the value of the resistive elements of those circuits that are a.c. coupled via series capacitors and on the voltage appearing between valve terminals during the non-conduction interval.

$$P_{V5} = 2\pi f^2 U_{v0}^2 C_{AC}^2 R_{AC} \left\{ \begin{array}{l} \dfrac{4\pi}{3} - \dfrac{\sqrt{3}}{2} + \dfrac{3\sqrt{3}m^2}{8} + \left(6m^2 - 12m - 7\right)\dfrac{\mu}{4} + \left(\dfrac{7}{8} + \dfrac{9m}{4} - \dfrac{39m^2}{32}\right)\sin 2\alpha + \\ \left[\left(\dfrac{7}{8} + \dfrac{3m}{4} + \dfrac{3m^2}{32}\right)\sin(2\alpha + 2\mu) - \left(\dfrac{\sqrt{3}m}{16} + \dfrac{3\sqrt{3}m^2}{8}\right)\cos 2\alpha + \dfrac{\sqrt{3}m}{16}\cos(2\alpha + 2\mu)\right] \end{array} \right\}$$

where

C_{AC} is the effective terminal-to-terminal value of valve damping capacitance, in farads (see figure 3);

R_{AC} is the effective terminal-to-terminal value of the associated series-connected damping resistance, in ohms (see figure 3).

C_{AC} shall be the design value of damping capacitance per level divided by the number of thyristor levels in a valve.

R_{AC} shall be the design value of damping resistor per level multiplied by the number of thyristor levels in a valve.

If the valve employs more than one damping or grading network that incorporates series-connected R-C branches, then each branch shall be evaluated separately and the results summed.

If energy is extracted from the R-C grading network to energize the thyristor firing and/or monitoring circuits, then either it shall be demonstrated that the additional losses are negligible or the additional loss shall be calculated separately and added to the figure obtained from the equation P_{V5}.

NOTE – Notes 1, 3 and 4 in 5.1.4 also apply to P_{V5}.

5.1.6 Damping loss per valve (change of capacitor energy term)

This loss component arises from the change in stored energy in the valve capacitances as a result of the step changes (ΔU) in the voltage blocked by the valve. Each step change incurs energy loss which equals $\frac{1}{2} C \times \Delta U^2$. The equation below is derived from the sum of the energies lost due to the 12 voltage jumps which take place during one cycle of blocking voltage (figure 4) multiplied by the system frequency.

$$P_{V6} = \frac{U_{v0}^2 \times f \times C_{HF} \times \left(7 + 6m^2\right)}{4} \left[\sin^2(\alpha) + \sin^2(\alpha + \mu)\right]$$

where

C_{HF} is the sum of the effective terminal-to-terminal capacitance of all capacitive grading network branches within the valve (whether incorporating series resistors or not), plus the total effective stray capacitance between valve terminals arising from externally connected equipment and the vicinity of the valve to ground and/or adjacent objects (see note 3). $C_{HF} = C_{AC} + C_S$ (see figure 3).

NOTE 1 – Notes 1, 3 and 4 in 5.1.4 also apply to P_{V6}.

NOTE 2 – The equation for P_{V6} produces overly pessimistic results for commutation overlaps whose length is shorter than 3 time-constants of the R-C damping network.

NOTE 3 – The external stray capacitance arises predominantly from the winding and bushings of the converter transformer (plus separate wall bushings if fitted), all of which can be measured at manufacture. Depending on the design, stray capacitance between the valve and the earth may also have to be included. Surge arresters, busbars and the valve structure contribute to the stray capacitance, but these contributions are small and may be neglected. Since the effective stray capacitance is different for each row of valves, the average value is used for loss calculation.

5.1.7 Turn-off losses per valve

These are additional losses generated in the thyristors and damping resistors due to reverse current flow in the thyristors at turn-off (see figure 8).

$$P_{V7} = Q_{rr} \times f \times \sqrt{2} \times U_{v0} \times \sin(\alpha + \mu + 2\pi \times f \times t_0)$$

where

Q_{rr} is the average value of thyristor stored charge, in coulombs;

t_0 is the time determined from the relationship

$$t_0 = \sqrt{\frac{Q_{rr}}{(di/dt)_{i=0}}}$$

where

$(di/dt)_{i=0}$ is the commutating di/dt measured at current zero, in amperes per second.

NOTE – The value of Q_{rr} used is the full integral of reverse current (see figure 8), not an approximate triangulation such as that proposed in IEC 60747-6. Q_{rr} is determined from production measurements on a statistically significant number of thyristors and, where necessary, is corrected to the junction temperature, $(di/dt)_{i=0}$ and reverse recovery voltage corresponding to the operating conditions for which the losses are being determined. It is important that the magnitude and the duration of the conduction current are large enough to achieve a full conduction of the thyristor junction.

5.1.8 Reactor loss per valve

Reactor loss consists of three components: resistive loss in the winding plus eddy current loss and hysteresis loss in the magnetic core. If an additional damping circuit is employed across the winding, it also incurs loss.

Reactor winding loss and the reactor core eddy current loss (and/or reactor damping resistor loss) are already accounted for in the equations for P_{V3} and P_{V6}.

Hysteresis loss shall be calculated as follows. A d.c. magnetization curve for the core material(s) shall be determined for the loop of excitation that an HVDC valve reactor normally experiences. This curve shall be established from a magnetizing force arising from not less than 1,5 times the peak of the reverse current I_{rr} at turn-off (see figure 8) in one polarity to well into the saturated region in the other, and back again. From the area enclosed by the loop, a characteristic hysteresis loss in joules per kilogram shall be determined and applied to the design of the reactor in question, i.e.

$$P_{V8} = n_L \times M \times k \times f$$

where

n_L is the number of reactor cores in a valve;

M is the mass of each core, in kilograms;

k is the characteristic loss, in joules/kilogram.

NOTE – If the saturation current level for the reactor is high in relation to the rated bridge current, and normal commutation di/dt is also high (corresponding to small overlap angles at rated conditions), then additional reactor core eddy current losses will be generated during the commutation periods. If this is the case, it should be demonstrated that these additional losses are either negligible or else within the allowance made in the loss declaration.

5.1.9 Total valve losses

Total operating losses per valve are given by the sum of the eight individual components specified above.

$$P_{VT} = \sum_{i=1}^{i=8} P_{Vi}$$

The total operating converter losses are equal to the losses per valve multiplied by the number of valves in the converter.

5.1.10 Temperature effects

All valve components have electrical characteristics that are temperature sensitive. However, it is a common occurrence that the only component with temperature-sensitive characteristics that can substantially affect valve losses is the thyristor itself.

Thyristor junction temperature T_j is determined as

$$T_j = T_c + P_j \times R_{\theta JC}$$

where

T_C is the temperature of the coolant calculated as the mean of the valve inlet and valve outlet temperatures;

P_j is the total power loss per thyristor, calculated as the sum of its individual components due to conduction, spreading, blocking and turn-off;

$R_{\theta JC}$ is the thermal resistance from the thyristor junction to the coolant.

5.1.11 No-load operation loss per valve

The no-load operation loss per valve is the sum of losses caused by the currents which are driven by the voltage blocked by the valve through the resistances of the valve. It consists of two terms. The first quantifies the loss in the resistances which are connected in parallel with the blocking thyristors, the second determines the loss in the resistances which are capacitively coupled. In no-load operation mode the valve blocks the sinusoidal waveform of the line to neutral voltage. Consequently:

$$P_{VSB} = \frac{U_{v0}^2}{3}\left(\frac{1}{R_{DC}} + \frac{R_{AC}}{Z_{AC}^2}\right)$$

where

$$Z_{AC} = \sqrt{R_{AC}^2 + \left(\frac{1}{2\pi \times f \times C_{AC}}\right)^2}$$

If the valve employs more than one grading network branch that incorporates series-connected R and C, then each branch shall be evaluated separately and the results summed.

If energy is extracted from the R-C grading network to energize the thyristor firing and/or monitoring circuits, then either it shall be demonstrated that the additional losses are negligible or the additional loss shall be calculated separately and added to the figure obtained from the equation P_{VSB}.

The total converter no-load operation losses are the no-load operation loss per valve multiplied by the number of valves in the converter.

5.2 Converter transformer losses

5.2.1 General

The current flowing through the windings of converter transformers contains harmonics whose magnitudes depend on the operating parameters of the converter station. The current-dependent load losses in the transformer due to the non-sinusoidal current waveshapes are greater than those that would occur with a sinusoidal current of the same r.m.s. value at fundamental frequency.

5.2.2 No-load operation losses

In no-load operation mode, with the transformer energized and the valves blocked, the transformer losses are the no-load losses. The no-load losses (core losses) shall be determined according to IEC 60076-1.

5.2.3 Operating losses

In the operating mode, the transformer operating losses shall be taken as the sum of the magnetizing losses (core losses) and the current-dependent (load) losses.

Under load-carrying conditions, harmonic voltages are imposed on the transformer. The core losses under load shall be considered equal to the no-load losses at the tap position corresponding to the load level considered, with nominal a.c. system voltage applied. The effect of the harmonic voltages on the magnetizing current of the transformer, relative to the effect of the fundamental frequency component of the voltage, is negligible.

The load losses of the transformer shall take into account both the fundamental frequency and the harmonic components of the current and shall be determined according to the following procedure:

a) measure the load losses P_1 at fundamental frequency f_1 (50 Hz or 60 Hz) according to IEC 60076-1;

b) calculate $P_{WE1} + P_{SE1} = P_1 - P_R$;

c) measure the load losses P_m at a higher frequency f_m equal to or greater than 150 Hz.

NOTE – A voltage source used for induced voltage tests is normally available. An acceptable accuracy is reached for currents as low as 10 % to 20 % of the rated current provided that stray flux distribution among metallic parts has been taken care of in the transformer design. If a reduced current is used, and the current is less than 10 %, P_m shall be recalculated to rated current.

d) calculate P_{WE1} and P_{SE1} based on the measurements at fundamental frequency and the higher frequency by solving

$$P_1 = P_R + P_{WE1} + P_{SE1}$$

$$P_m = P_R + P_{WE1} \times (f_m/f_1)^2 + P_{SE1} \times (f_m/f_1)^{0,8};$$

e) the total service load losses shall be calculated for each valve winding as follows:

$$P = P_{R} + P_{WE1} \times \sum_{n=1}^{n=49} (I_n / I_N)^2 \times (f_n / f_1)^2 + P_{SE1} \times \sum_{n=1}^{n=49} (I_n / I_N)^2 \times (f_n / f_1)^{0,8}$$

where

P_1 represents the total load losses at fundamental frequency (50 Hz or 60 Hz);

I_N is the rated current;

I_n is the r.m.s. current at harmonic n;

P_R represents the ohmic losses at rated current;

P_{SE1} represents the stray losses in structural parts (excluding windings) at fundamental frequency;

P_{WE1} represents the eddy losses in windings at fundamental frequency;

P_m represents the total load losses at frequency m;

n is the harmonic order;

f) the operating losses are calculated as the sum of the no-load losses (see 5.2.2) and the total service load losses as defined above.

NOTE 1 – The equation for the total service load losses is valid for all harmonic numbers. However, the non-characteristic harmonics are small compared to the characteristic harmonics and should be neglected in the determination of the losses.

NOTE 2 – With the harmonic current spectrum specified in clause A.1, the above method is valid for two-winding transformers or for three-winding transformers whose construction is such that the coupling between valve windings is negligible (for example where the line winding is split into two halves, one next to each valve winding). For other transformer arrangements a similar method may be used, with due care, but the harmonic current spectrum in the line windings may differ from that given in clause A.1.

5.2.4 Auxiliary power losses

The auxiliary power losses of the converter transformer shall be included in the auxiliary power energy consumption of the total converter station (see 5.8). They shall be measured either separately during a factory test or during measurement of the converter station auxiliary power consumption.

5.3 AC filter losses

5.3.1 General

The a.c. filters in an HVDC converter station provide a low-impedance shunt for the harmonic currents generated by the converter. The a.c. filters may comprise active filters, passive filters or a combination thereof.

The methods described below assume that the a.c. filters are connected directly to the a.c. system busbar on the line side of the converter transformer. Where this is not the case, as for instance with filters connected to a tertiary winding of the converter transformer, the method is still valid but the harmonic currents in the filters shall be adjusted as required by the a.c. filter connection point.

For purposes of loss determination, the converter shall be modelled as a generator of harmonic currents and the a.c. system shall be assumed to be open-circuited so that all harmonic currents from the HVDC converters are considered to flow into the a.c. filters.

The harmonic current flowing in each filter branch shall be calculated from the total converter harmonic current and shall be used as a basis for determining the losses in each filter component. When active filters are used, the losses incurred by their presence shall be included and the calculation method documented by the supplier.

When the converter is operating, the determination of a.c. filter losses shall be based on the characteristic harmonic currents of the converter, which shall be calculated for each load level and with consistent operating parameters (see 4.3). For calculation of the converter harmonic currents, the formula described in clause A.2 shall be used.

In the no-load operation mode, a.c. filters are not usually connected to the a.c. system and, therefore generate no losses. In the case where a.c. filters are energized while the converter is in no-load operation mode only the fundamental frequency losses shall be considered.

5.3.2 AC filter capacitor losses

The fundamental frequency losses in the filter capacitors shall be determined in accordance with IEC 60871-1. The three-phase Mvar rating of the capacitor bank shall be calculated from the capacitance value and the fundamental frequency voltage across the capacitor bank. The losses due to harmonic currents are very small and shall be neglected.

5.3.3 AC filter reactor losses

The fundamental and harmonic currents in the filter reactors shall be considered. The impedance of the reactor at fundamental frequency and the quality factors at the fundamental and harmonic frequencies shall be measured at the factory and corrected to the maximum operating temperature of the winding. The reactor losses shall then be determined by the equation

$$P = \sum_{n=1}^{n=49} \frac{I_n^2 \times X_n}{Q_n}$$

where

n is the harmonic order;

I_n is the calculated r.m.s. current through the reactor at the nth harmonic, in amperes;

X_n is the reactor reactance at the nth harmonic, $X_n = n \times 2\pi f \times L$, in ohms;

L is the reactor inductance, in henrys;

f is the a.c. system fundamental frequency;

Q_n is the average quality factor for all reactors of the same item measured at the nth harmonic.

5.3.4 AC filter resistor losses

The losses in the filter resistors shall be calculated for the fundamental and harmonic currents together. The resistance value of the resistor shall be determined by factory measurements and corrected to the operating temperature of the resistor. The current of each harmonic through the filter resistor shall be calculated. The losses in each resistor are obtained by the formula

$$P = R \times \sum_{n=1}^{n=49} I_n^2$$

where

R is the resistor value, in ohms;

I_n is the r.m.s. value of the nth harmonic current through the resistor, in amperes.

5.3.5 Total a.c. filter losses

The total a.c. filter losses shall be obtained by summing the losses of all capacitors, reactors, and resistors for filters which are energized at the corresponding load level of the converters.

5.4 Shunt capacitor bank losses

Shunt capacitors are sometimes used in addition to harmonic filters to provide reactive support to the a.c. system. Power losses in shunt capacitor banks shall be determined for those load levels of the converter station at which such banks are connected to the a.c. bus.

The fundamental frequency losses in the shunt capacitor bank shall be determined in accordance with IEC 60871-1. The three-phase Mvar rating of the capacitor bank shall be calculated from the capacitance value and the fundamental frequency voltage across the capacitor bank. The losses due to harmonic currents are very small and shall be neglected.

5.5 Shunt reactor losses

Shunt reactors may be connected to the a.c. bus of an HVDC converter station to compensate for capacitive currents from a.c. harmonic filters, particularly at light load. Their duty does not differ from conventional applications in a.c. transmission systems. Therefore, losses of shunt reactors in HVDC converter stations shall be measured during factory tests in accordance with IEC 60289 and corrected to the maximum winding temperature, excluding hot spots, calculated for the standard ambient conditions (see 4.3). For oil-insulated reactors, the standard winding temperature of 75 °C shall be used.

Shunt reactor losses shall be included in the total converter station losses for those load levels at which it is intended that shunt reactors will be connected to the a.c. bus.

If forced cooling is used, the cooling equipment power consumption shall be included in the auxiliary power consumption of the total converter station (see 5.8).

5.6 DC smoothing reactor losses

The current through the smoothing reactor is direct current with superimposed harmonics.

During no-load operation conditions, the smoothing reactor current is zero. Therefore losses do not occur.

The d.c. component of the smoothing reactor losses shall be established from factory tests according to IEC 60289 and IEC 60076-1.

The winding losses due to harmonic currents shall be determined by calculation. The calculation shall use the harmonic current amplitudes applicable to the appropriate load level and the corresponding harmonic resistance. The harmonic currents shall be calculated in accordance with clause A.4. The harmonic resistance shall be measured.

If a tanked construction with an iron core is used, the magnetization losses shall be calculated as:

$$P_m = (0{,}125 \times k_h + 0{,}125 \times k_e) \times P_d$$

where

P_m represents the magnetization losses, in watts;

P_d represents the direct current losses, in watts;

$k_h = \sum_{n=12}^{n=48} k_{hn}$ is the hysteresis losses component;

$k_e = \sum_{n=12}^{n=48} k_{en}$ is the eddy current losses component;

$k_{hn} = (I_n/I_d) \times n$;

$k_{en} = (I_n/I_d)^2 \times n^{0,5}$.

The total operating losses shall be the sum of losses due to direct current, losses due to harmonic currents and, where applicable, core magnetizing losses.

Auxiliary power losses of the smoothing reactor shall be included, where applicable, in the auxiliary power consumption of the total converter station (see 5.8). They may be measured separately during factory tests or during measurements of the converter station auxiliary power consumption.

5.7 DC filter losses

5.7.1 General

The principal function of the d.c. filters, in conjunction with the d.c. smoothing reactor, is to provide a low-impedance shunt for the harmonic currents generated by the converter, thus reducing the level of harmonic currents on the d.c. line and preventing noise generation in adjacent open-wire communication systems. The d.c. filter may be configured either as a single branch or as several filter branches, depending on system requirements. The d.c. filters may comprise active filters, passive filters or a combination thereof.

DC filters are connected between the high- and low-voltage terminals of the converter. Under no-load operation conditions, the d.c. filter current and voltage are both zero; therefore, losses do not occur.

When the converter is operating, the d.c. filter losses shall be determined for normal operating parameters, at the appropriate load level, using factory loss measurements and calculated harmonic currents. The harmonic currents through the filters shall be calculated by representing the converter as a voltage source and an impedance. For calculation of the converter harmonic voltages, the formulae according to clause A.3 shall be used. The smoothing reactors and the d.c. line/cable shall be represented with their actual impedances. For the calculation it shall be assumed that the a.c. system operates at nominal frequency and the filter components are at their nominal values. When active filters are used, the losses incurred by their presence shall be included and the calculation method documented by the supplier.

5.7.2 DC filter capacitor losses

Losses in the d.c. filter capacitors comprise losses in the d.c. grading resistors and harmonic losses in the capacitors. Losses due to the harmonic current in the capacitor bank are very small because of the low power factor and shall be neglected.

The losses in the grading resistors shall be calculated by using the total resistance of the capacitor bank as determined from the mean value of all grading resistors per capacitor unit obtained from production tests, and the capacitor bank configuration, using

$$P = \frac{U^2}{R}$$

where

U is the operating capacitor bank d.c. voltage, in volts;

R is the total bank resistance, in ohms.

5.7.3 DC filter reactor losses

The reactor losses shall be determined by calculating the harmonic currents in the reactor for the appropriate load level and corresponding operating parameters (see 4.3) and by measuring the reactor reactance and quality factor at the harmonic frequencies during factory tests, and corrected to the maximum operating temperature of the winding. The reactor losses are given by the formula

$$P = \sum_{n=12}^{n=48} \frac{I_n^2 \times X_n}{Q_n}$$

where

n is the harmonic order;

I_n is the calculated r.m.s. current through the reactor at the nth harmonic, in amperes;

X_n is the reactor reactance at the nth harmonic, in ohms;

Q_n is the quality factor measured at the nth harmonic.

5.7.4 DC filter resistor losses

The resistor losses shall be calculated considering all harmonic currents together. The resistance value of the resistor R shall be determined by factory measurements.

The r.m.s. value of the current of each harmonic through the resistor shall be calculated for the appropriate load level of the converter station and corresponding operating parameters (see 4.3). The losses in each resistor are obtained by the formula

$$P_R = R \times \sum_{n=12}^{n=48} I_n^2$$

where

R is the resistance value, in ohms;

I_n is the calculated r.m.s. current through the resistor at the nth harmonic, in amperes.

5.7.5 Total d.c. filter losses

The total d.c. filter losses shall be obtained by summing the losses of all capacitors, reactors, resistors and active devices, where applicable, that make up the d.c. filters.

5.8 Auxiliaries and station service losses

The auxiliary power consumed by the HVDC converter station depends on station service facilities, operating requirements and ambient conditions. Moreover, it is subject to variation with time as intermittent loads such as heating, cooling, lighting and maintenance equipment are utilized. The purchaser shall define the extent of the auxiliary services to be included in the loss evaluation.

The total station auxiliary losses shall be determined for no-load operation mode and for the appropriate load level(s) of the station. The losses shall be determined under normal steady-state operating conditions by direct measurements on the main feeder(s) at each source.

Station service auxiliaries used only under special circumstances, for example during maintenance outages, short-time overload or transient disturbances, shall not be considered in the evaluation of auxiliary losses.

To account for load variations with time due, for example, to intermittent operation of cooling pumps or fans or to heating and lighting loads which are required only at certain times of the day, a series of measurements shall be taken over a defined time interval and the results averaged.

If it is not practical to perform the measurement on auxiliary power consumption at a constant ambient temperature of 20 °C, an appropriate adjustment shall be made to those loads (such as cooling equipment) which are sensitive to the ambient temperature. The calculation shall be documented.

In cases where the feeder(s) for the auxiliary systems also supply equipment which is not within the responsibility of the supplier, the load(s) of this equipment shall be measured separately and subtracted from the overall loss measurement for contractual purposes.

If the design of the auxiliary system is such that the total auxiliary power consumption cannot practically be determined by direct measurement, then an alternative calculation procedure may be agreed between purchaser and supplier. In this case, the calculation procedure shall be clearly documented.

5.9 Radio interference/PLC filter losses

In addition to the a.c. and d.c. harmonic filters normally required at an HVDC station, certain applications require further equipment to prevent radio interference (RI) or interference with power line carrier (PLC) systems.

Such equipment may consist of series reactors in the a.c. or d.c. connections (with or without tuning capacitors connected in parallel), shunt branches or a combination thereof.

Losses in shunt branches are small and shall be neglected.

For series filters, only the losses in the reactor shall be considered. The reactor losses shall be calculated in accordance with the following formulae:

$$P = \sum_{n=1}^{n=49} \frac{I_n^2 \times X_n}{Q_n}$$

for filters in the a.c. connections, or

$$P = I_d^2 \times R_{\text{PLC}} + \sum_{n=12}^{n=48} \frac{I_n^2 \times X_n}{Q_n}$$

for filters in the d.c. connections

where

R_{PLC} is the d.c. resistance of the reactor, in ohms;

n is the harmonic order;

I_n is the calculated current through the reactor at the nth harmonic, in amperes;

X_n is the reactor reactance at the nth harmonic, in ohms;

Q_n is the quality factor measured at the nth harmonic.

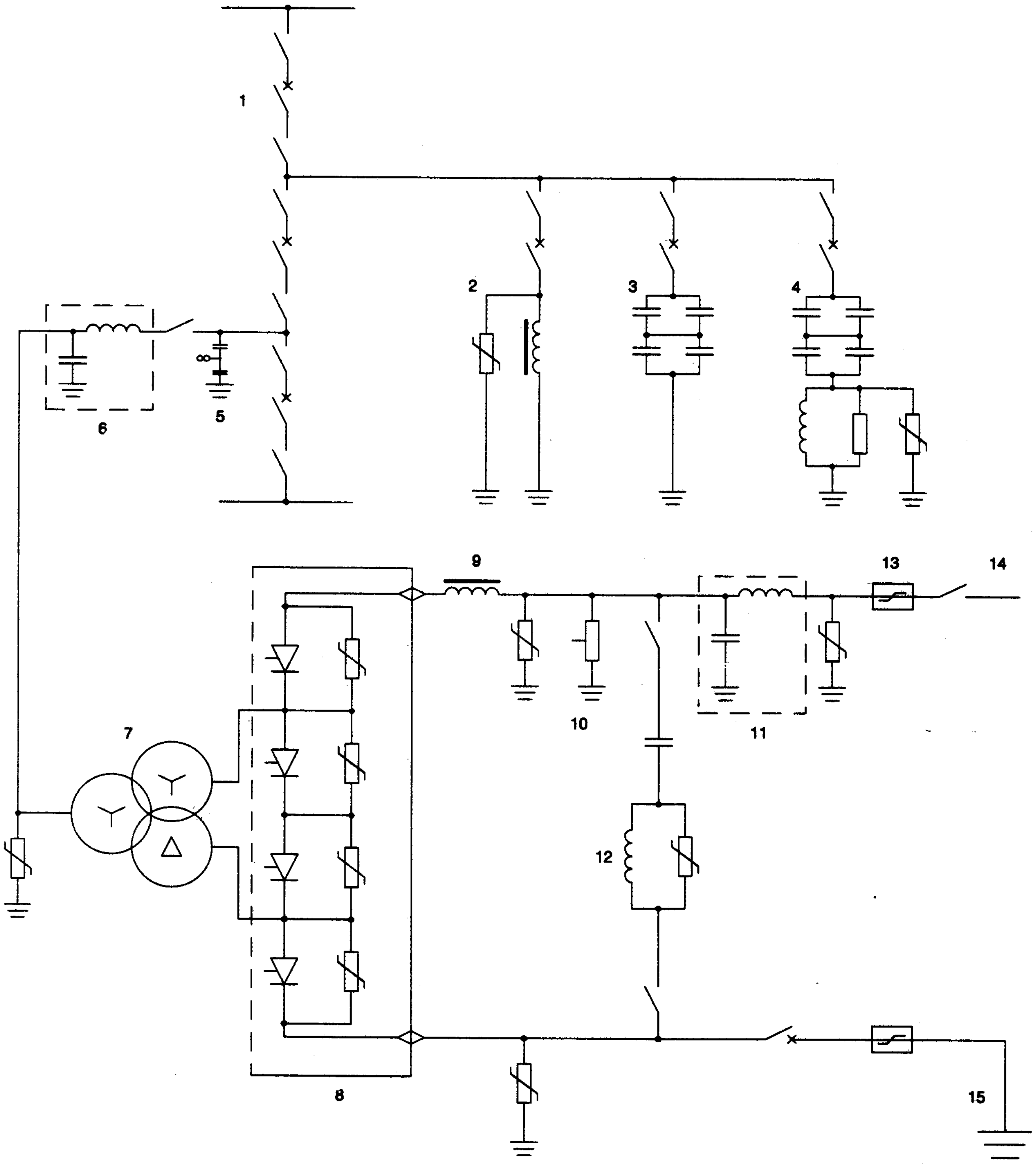
When a.c. series filters are located on the a.c. system side of the a.c. harmonic filters, only the fundamental frequency (n = 1) component of current shall be considered. Where a.c. series filters are located between the shunt a.c. harmonic filters and the converter transformers, or between the converter transformers and the valves, then both the fundamental frequency and characteristic harmonic (up to n = 49) components of current shall be considered.

Harmonic currents shall be calculated in accordance with clauses A.1 and A.2 or (for filters on the d.c. side) clause A.4, as appropriate.

5.10 Other equipment losses

The losses caused by the remaining equipment, such as surge arresters, instrument transformers, switchgear, etc., shall be neglected. They are negligible in comparison with the main equipment losses discussed in subclauses 5.1 through 5.9, and neglecting them will not significantly affect the total converter station losses.

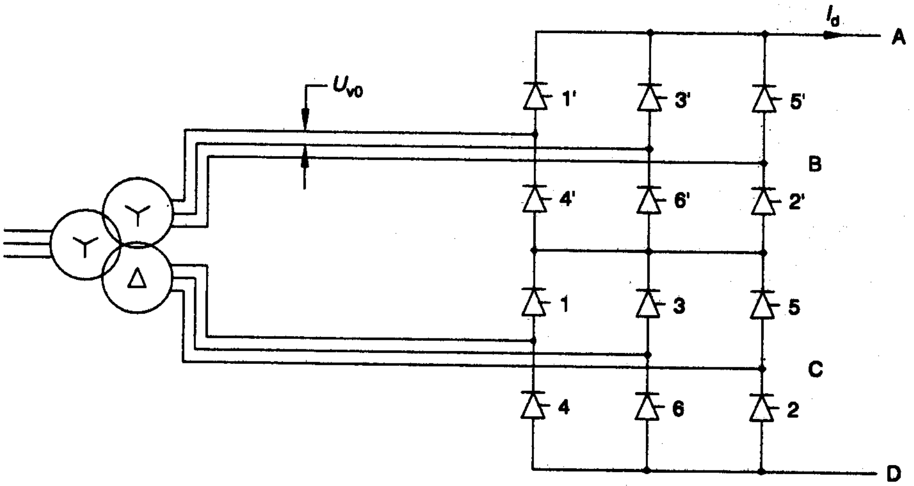
The losses of special equipment in a particular converter station, which are not included in the typical converter station considered in this standard, shall be determined for each of the operating conditions of interest. The determination shall be based on the characteristics of the special equipment and sound engineering practice.



Key

1	AC switchyard	9	DC smoothing reactor
2	Shunt reactor bank	10	Voltage divider
3	Shunt capacitor bank	11	PLC filter
4	AC filter bank	12	DC filter
5	Capacitor voltage transformer	13	DC current measuring device
6	PLC filter	14	Pole line
7	Converter transformer	15	Ground electrode
8	Valve hall		

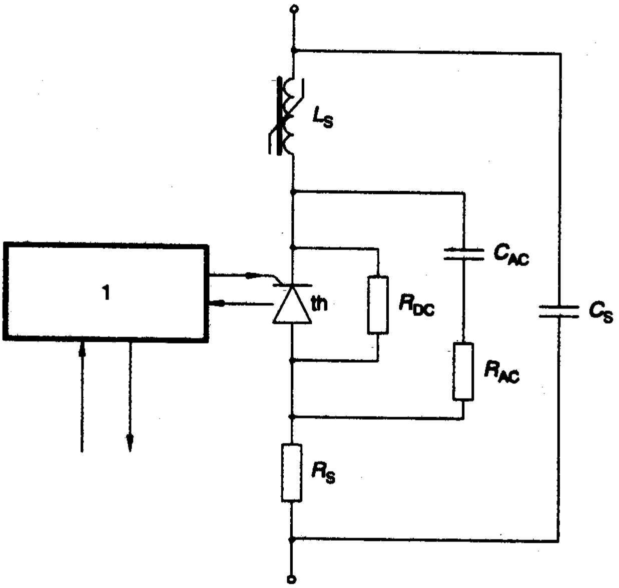
Figure 1 – Typical high-voltage direct current (HVDC) equipment for one pole (auxiliary equipment is not shown)



Key

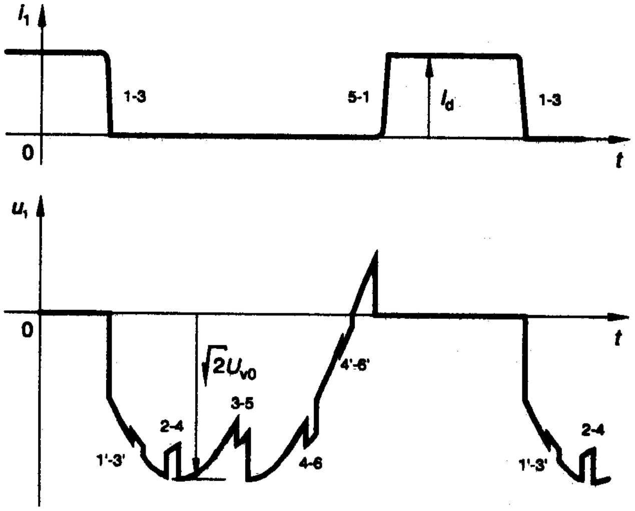
A High-voltage d.c. terminal
B Upper bridge
C Lower bridge
D Low voltage d.c. terminal

Figure 2 – Simplified three-phase diagram of an HVDC 12-pulse converter



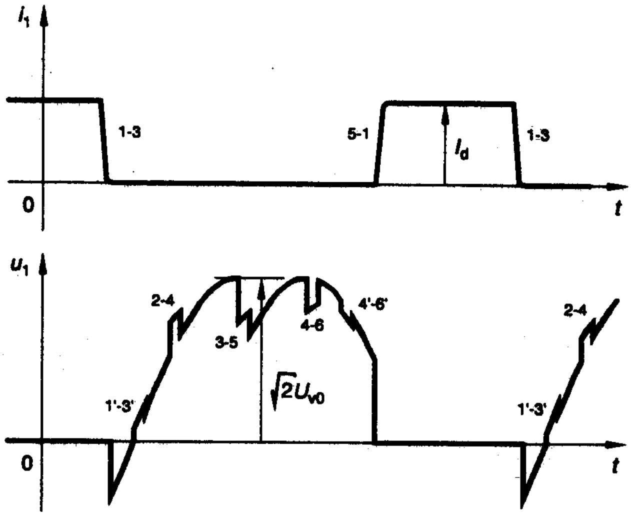
1 Control and monitoring

Figure 3 – Simplified equivalent circuit of a typical thyristor valve



$\alpha = 20°$ $\mu = 10°$

Figure 4a – Rectifier operation



$\gamma = 20°$ $\mu = 10°$

Figure 4b – Inverter operation

Figure 4 – Current and voltage waveforms of a valve operating in a 12-pulse converter (commutation overshoots are not shown)

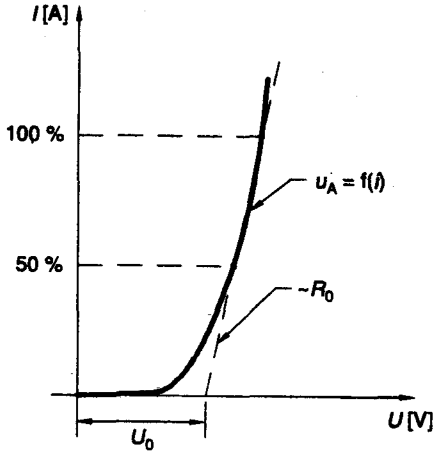


Figure 5 – Thyristor on-state characteristic

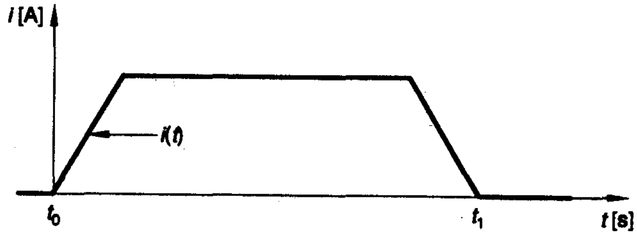
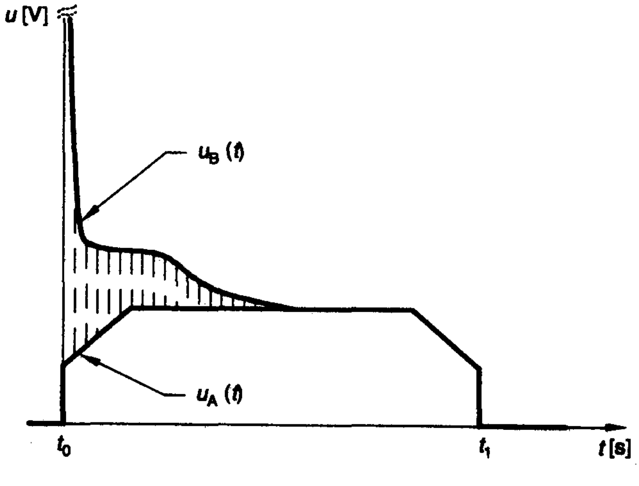


Figure 6a – Conduction current

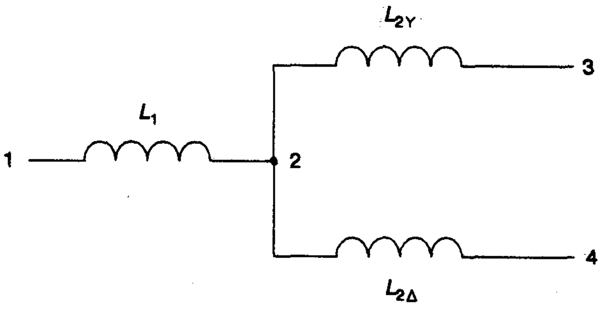


A Ideal thyristor with a conduction characteristic determined by U_0 and R_0 (as per figure 5)

B Real thyristor which displays the spreading effect

Figure 6b – Voltage drop across an ideal thyristor A or a real thyristor B

Figure 6 – Conduction current and voltage drop



Key

1 From the source of the commutating voltage
2 Point of common coupling
3 To the valves
4 To the valves

Figure 7 – Distribution of commutating inductance between L_1 and L_2

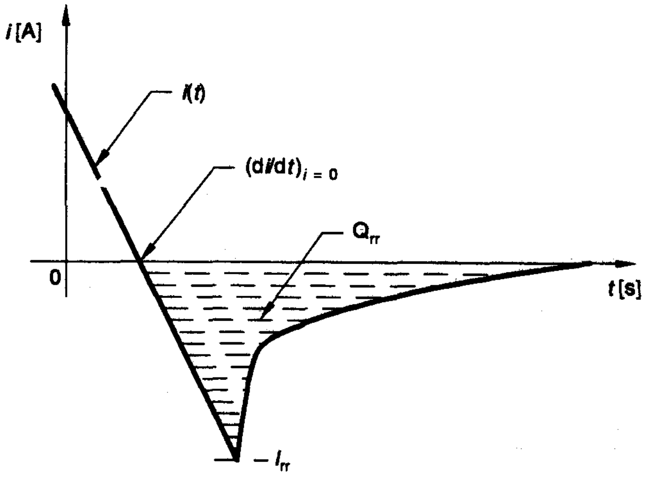


Figure 8 – Thyristor current during reverse recovery

Annex A
(normative)

Calculation of harmonic currents and voltages

A.1 Harmonic currents in converter transformers

The r.m.s. value of the six-pulse characteristic harmonic currents in each valve side terminal of the converter transformer is

$$I_n = \frac{\sqrt{6} \times I_d \times F_1}{\pi \times n}$$

where

n is the characteristic harmonic order, $n = k \times 6 \pm 1$, k being a positive integer in the range $1 \leq k \leq 8$

$$F_1 = \frac{\left(k_1^2 + k_2^2 - 2k_1 \times k_2 \times \cos(2\alpha + \mu)\right)^{1/2}}{\cos\alpha - \cos(\alpha + \mu)}$$

$$k_1 = \frac{\sin\left((n-1) \times \frac{\mu}{2}\right)}{n-1}$$

$$k_2 = \frac{\sin\left((n+1) \times \frac{\mu}{2}\right)}{n+1}$$

A.2 Harmonic currents in the a.c. filters

The r.m.s. value of the 12-pulse characteristic harmonic currents on the line side of the converter transformer is

$$I_n = \frac{\sqrt{6} \times I_d \times F_1}{\pi \times n} \times \frac{U_v}{U_L} \times 2$$

where

n is the characteristic harmonic order, $n = k \times 12 \pm 1$, k being a positive integer in the range $1 \leq k \leq 4$

U_v/U_L is the converter transformer voltage ratio, valve-side voltage divided by line-side voltage (including the actual tap position)

$$F_1 = \frac{\left(k_1^2 + k_2^2 - 2k_1 \times k_2 \times \cos(2\alpha + \mu)\right)^{1/2}}{\cos\alpha - \cos(\alpha + \mu)}$$

$$k_1 = \frac{\sin\left((n-1) \times \frac{\mu}{2}\right)}{n-1}$$

$$k_2 = \frac{\sin\left((n+1) \times \frac{\mu}{2}\right)}{n+1}$$

A.3 Harmonic voltages on the d.c. side

The r.m.s. value of the harmonic voltages from a 12-pulse bridge is

$$U_n = \frac{6\sqrt{2}}{\pi} \times U_{v0} \times F_2$$

where

n is the characteristic harmonic number, $n = k \times 12$, k being a positive integer in the range $1 \leq k \leq 4$

$$F_2 = \frac{\left(k_3^2 + k_4^2 - 2k_3 \times k_4 \times \cos(2\alpha + \mu)\right)^{1/2}}{2}$$

$$k_3 = \frac{\cos\left((n+1) \times \frac{\mu}{2}\right)}{n+1}$$

$$k_4 = \frac{\cos\left((n-1) \times \frac{\mu}{2}\right)}{n-1}$$

If more than one 12-pulse converter is connected in series on the d.c. side, the harmonic voltage is U_n multiplied by the number of series-connected 12-pulse converters.

A.4 DC side harmonic currents in the smoothing reactor

The d.c. side harmonic currents through the smoothing reactor are calculated by representing the converter with a voltage source with harmonic voltages in accordance with clause A.3. The converter impedance and the smoothing reactor, the d.c. filters and d.c. line/cable shall be represented by their actual impedances.

Annex B
(informative)

Typical station losses

Typical values of losses are given below for information purposes:

Item	Typical losses at nominal operating conditions %
Thyristor valves	25 – 45
Converter transformers	40 – 55
AC filters	4 – 10
Shunt capacitors (if used)	0,5 – 3
Shunt reactors (if used)	2 – 5
Smoothing reactor	4 – 13
DC filters	0,1 – 1
Auxiliaries	3 – 10
Total	100

The total no-load operation losses range from 10 % to 20 % of the operating losses at nominal operating conditions.

Annex C
(informative)

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CORRIGENDUM

Page 8

5.1.4 DC voltage-dependent loss per valve

Equation P_{v4}

Instead of:

$$P_{V4} = \frac{U_{v0}^2}{2\pi \ R_{DC}} \left\{ \frac{4}{3} + \frac{\sqrt{3}}{4}[\cos(2\alpha)+\cos(2\alpha+2\mu)] + \frac{6m^2-12m-7}{8}[\sin(2\alpha)-\sin(2\alpha+2\mu)+2\mu] \right\}$$

Read:

$$P_{V4} = \frac{U_{v0}^2}{2\pi \ R_{DC}} \left\{ \frac{4}{3}\pi + \frac{\sqrt{3}}{4}[\cos(2\alpha)+\cos(2\alpha+2\mu)] + \frac{6m^2-12m-7}{8}[\sin(2\alpha)-\sin(2\alpha+2\mu)+2\mu] \right\}$$

(*Continued from second cover*)

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60633 (1998) Terminology for high-voltage direct current (HVDC) transmission	IS 14801 : 2000 Terminology for high-voltage direct current (HVDC) transmission	Identical
IEC 60700-1 (1988) Thyristor valves for high voltage direct current (HVDC) power transmission — Part 1 : Electrical testing	IS 14911 (Part 1) : 2001 Thyristor valves for high-voltage direct current (HVDC) power transmission: Part 1 Electrical testing	do
IEC 60871-1 (1999) Shunt capacitors for a.c. power systems having a rated voltage above 1 000 V — Part 1 : General performance, testing and rating — Safety requirements — Guide for installation and operation	IS 13925 (Part 1) : 1998 Shunt capacitors for a.c. power systems having a rated voltage above 1 000 V: Part 1 General performance, testing and rating — Safety requirements — Guide for installation and operation	Technically Equivalent

Technical Corrigendum of International Standard has been given at the end of this publication.

The technical committee responsible for the preparation of this standard has reviewed the provisions of the following International Standard and decided that they are acceptable for use in conjunction with this standard:

International Standard	*Title*
IEC 60076-1 (1993)	Power transformers — Part 1 : General
IEC 60747-6 (1983)	Semiconductor devices — Discrete devices — Part 6 : Thyristors

Only the English language text in the International Standard has been retained while adopting it as an Indian Standard.

For the purpose of deciding whether a particular requirement of this standard is complied with the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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Amendments Issued Since Publication

Amend No.	Date of Issue	Text Affected

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